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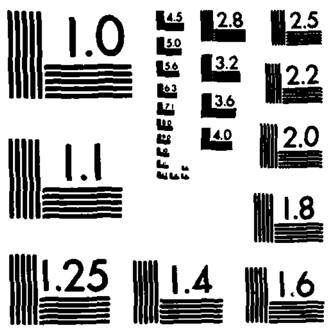

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SIMULATION OF BUSY TONE MULTIPLE ACCESS MODES IN MULTIHOP PACKET RADIO NETWORKS*

By

Fouad A. Tobagi and David H. Shur

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In this study we examine via simulation, the performance of the ALOHA, CSMA, BTMA, and CDMA channel access schemes in multihop packet radio systems. The performance of CSMA, which is efficient in fully-connected environments, is shown to degrade significantly in the presence of hidden nodes. The BTMA protocol attempts to overcome the hidden node problem and to obtain

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Abstract

In this study we examine via simulation, the performance of the ALOHA, CSMA, BTMA, and CDMA channel access schemes in multihop packet radio systems. The performance of CSMA, which is efficient in fully-connected environments, is shown to degrade significantly in the presence of hidden nodes. The BTMA protocol attempts to overcome the hidden node problem and to obtain efficient channel utilization in multihop environments by having nodes transmit a busy tone when they are busy receiving. In an example of a six node ring topology, we compare the performance of the CSMA and ALOHA schemes with four variants of BTMA. The highest throughput is achieved by II-BTMA and C-BTMA, which both significantly outperform the CSMA and ALOHA schemes. Our conclusion is that the improvement in bandwidth utilization achieved by BTMA in environments with hidden nodes, is expected to more than compensate for the cost of the busy tone channel.

Key Words and Phrases: multihop packet radio systems, packet switching, channel access protocols, ALOHA, carrier sense multiple access, busy tone, code division multiple access, performance, throughput, delay.

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1. Introduction

A packet radio network is a collection of geographically distributed, possibly mobile packet radio units (PRU's), communicating with each other over a shared broadcast radio channel. Data originates at some PRU's (referred to as sources), is destined for other PRU's (referred to as destinations) and is transmitted in packetized form. Since a radio transmitter may be unable to reach its destination due to power limitation and because the topology may include obstacles that are opaque to radio signals, PRU's also act as repeaters which relay packets in a store-and-forward manner between sources and destinations. So a message transmitted by the source might travel over many hops before reaching the destination.

There are many variables that need to be considered in the design of packet radio systems. Some of these are determined by the general objectives of the system. For example, all devices employ omnidirectional antennas in order to facilitate communications among mobile users. Other design variables have to be optimally selected so as to achieve the most cost-effective design. Among the variables to be selected are: network topology, which consists of the number of devices and how they are configured; the modulation and data encoding schemes used on the radio channel; the channel access policy by which the radio devices access the shared radio channel; the routing and flow control protocols which determine the flow of internal traffic in the network; and finally the nodal design which includes the selection of the storage capacity at each node and the buffer management strategy in use. In this report we will be concentrating on one of these design variables, namely the channel access policy.

Many access schemes have been devised which allow a set of geographically distributed users to access a common channel. As discussed in [16] these schemes differ in several respects namely the static or dynamic nature of the bandwidth allocation, the centralized or distributed nature of the decision making process, and the degree

of adaptivity to changes in user demands. Accordingly they are grouped into different classes out of which, given the mobile radio environment, the class of random access techniques offers the desired feature of simplicity in providing access to the channel in a distributed dynamic fashion. The simplest random access protocol is ALOHA [16,17], which permits users to transmit any time they desire. Under this protocol, the overlap in time and space of several transmissions which may occur on the shared channel, may induce significant errors in some or all of these transmissions, thus resulting in low channel efficiency. Carrier sense multiple access (CSMA) attempts to alleviate this problem by requiring the transmitter to sense the state of the channel (busy or idle) prior to transmitting and to inhibit transmission if the channel is sensed busy [13]. Analyses of these access schemes have previously focused mainly on single hop environments, assuming that all nodes are within range and in line-of-sight of each other. In such environments, and when in addition the propagation delay is small compared to the transmission time of a packet, analysis has clearly demonstrated the high channel utilization of CSMA and its superiority over the ALOHA schemes [13]. However analysis has also shown that CSMA suffers severe degradation when *hidden nodes* are present (i.e. when all nodes are not within range and in line-of-sight of each other) [14]. This situation is clearly met in multihop packet radio networks and hence in such networks CSMA is expected to perform rather poorly. The busy tone multiple access scheme (BTMA) attempts to overcome the hidden node problem by having a node transmit a busy tone when it is busy receiving, thus blocking its neighbors from interfering with its reception [1,14].

An alternative solution to the problem of collisions in multiacess/broadcast networks is based on spread spectrum and code division techniques. With these techniques the number of collisions may be reduced by using different orthogonal signalling codes in conjunction with matched filters at the intended receivers. Multiple orthogonal codes are obtained at the expense of increased bandwith (in order to spread the waveforms). Code division techniques can be imbedded in random access schemes giving rise to schemes known as spread spectrum multiple access (SSMA) and code division multiple

access (CDMA) [18]. Such schemes can be implemented by assigning a unique code to each node. Nodes then wishing to transmit to a particular node must utilize the code assigned to that node.

Relatively little work has been done on the development of analytic models for multihop networks. Recently some significant advances have been made in [2 - 7]. However, the models considered are restrictive as to the topological configurations considered, or the access schemes analyzed, or the performance measures obtained. For example in [2] and [3] the topology was restricted to a two hop centralized configuration; in [4], [5] and [6] the model is restricted to exponential packet lengths, zero propagation delay and gives no information about packet delay; in [7] only the slotted ALOHA protocol is considered. The difficulty in dealing with the general problem analytically, and the limitations of the analytic models so far devised has motivated us to write a general purpose simulation program to investigate BTMA modes and to compare them to ALOHA, CSMA and CDMA modes .

The program is written in PASCAL and is modular and extendible. The topology, routing scheme, buffer capacity, packet parameters and traffic parameters are *all* inputs to the program. It is used to give insight into the behavior of the various protocols by comparing them under identical conditions for all other design variables. The program has additional value in that it can also be used to verify approximate analytic models and to test the effect of simplifying assumptions.

The remainder of the report is structured as follows: section 2 explicitly describes the hidden node problem and the busy tone solution. Section 3 presents a precise description of the various protocols considered in this study, namely the ALOHA, CSMA,. BTMA, and CDMA protocols. Section 4 describes the essential variables considered in the simulation model of packet radio systems and the measures of system performance by which the protocols are evaluated. Section 5 describes an example of a network which was simulated and discusses the numerical results obtained. Finally Appendix 1 discusses the implementation of the simulation model, the validation of the

2. The Hidden Node Problem in Multihop Packet Radio Networks and the Busy Tone Solution

In this section we describe the hidden node problem, show how it degrades the performance of CSMA and describe the busy tone solution.

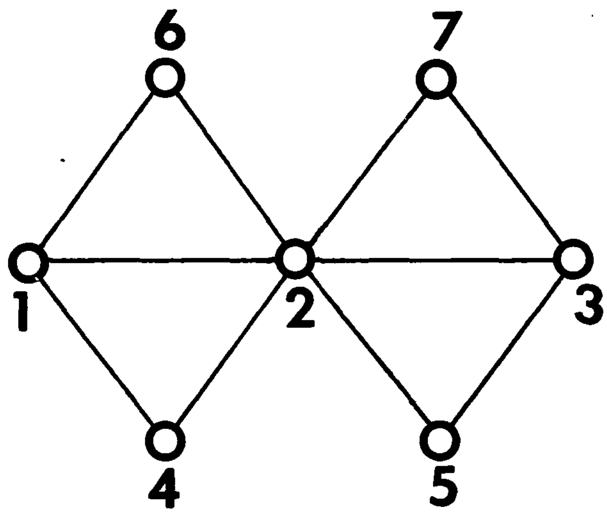

Figure 1: Example of a network with hidden nodes.

Consider for example the network depicted in figure 1. Connectivity between two nodes is denoted by a line joining those two nodes. For any node i, the set $N(i)$ is the collection of all nodes connected to it including itself. Let $N^*(i) = N(i) - i$. The elements of $N^*(i)$ are called neighbors of i.

For a collection of nodes A we define $N(A)$ to be

$$N(A) = \bigcup_{i \in A} N(i).$$

We let $N^2(A) \triangleq N(N(A))$. A node j is said to be hidden with respect to a node i iff $j \in N^2(i) - N(i)$.

Consider that the CSMA protocol is in effect and suppose node 1 is transmitting to node 2. Then suppose that during node 1's transmission node 7 also decides to

Consider that the CSMA protocol is in effect and suppose node 1 is transmitting to node 2. Then suppose that during node 1's transmission node 7 also decides to transmit a packet in its buffer to node 2. Despite carrier sensing, node 7 is unable to detect the transmission of node 1 and will transmit and cause a collision (unless some form of capture is in effect or orthogonal codes are used).

The problem of collisions among hidden nodes can be alleviated by the use of a busy tone, which is emitted by a node to indicate it is currently receiving a packet. This busy tone inhibits the node's neighbors from transmitting to it. This technique does not prevent all possible collisions since as with CSMA there is a vulnerable period in which collisions may occur. This is the time taken from the beginning of the packet transmission until the busy tone is detected by the neighbors of the destination. A pessimistic upper bound often assumed for this vulnerable period is twice the maximum propagation delay between pairs of neighboring nodes in the network.

3. Description of the Channel Access Protocols

We describe in this section the various channel access protocols considered in this report. These are the ALOHA, CSMA, BTMA, and CDMA schemes. We also describe what is meant by the term capture and how it applies to the different protocols.

The term capture refers to the ability of a receiver to successfully receive a packet destined to it, in spite of the presence of other overlapping signals on the same channel. By perfect capture, we mean that capture is achieved independent of the number of overlapping signals on the channel and their separation in terms of time of arrival. Zero capture refers to that situation in which any overlap of transmissions results in mutual destructive interference. In this study perfect capture is assumed for the CDMA protocol, while zero capture is assumed for all the other protocols.

In the event of a packet collision, or if a packet transmission is inhibited by the operation of the protocol, the packet is rescheduled for transmission at some random time in the future, according to some probability distribution referred to as

the rescheduling distribution.

We now outline the individual protocols.

Pure ALOHA:

In this mode, it is assumed that a node is allowed to transmit iff it is not already transmitting. This implies reception of a packet may be aborted if a packet transmission at that node is scheduled during the time of reception.

Slotted ALOHA:

Under this protocol, the time axis is considered to be universal for all nodes and divided into equally sized slots. Due to the non-zero propagation delay among nodes, in order to have a universal slotted time axis, the slot size must equal the packet transmission time plus a 'guard band' equal to the maximum of the propagation delays between pairs of neighboring nodes in the network. A node with a packet scheduled for transmission in a particular slot transmits that packet, synchronizing the start of transmission to coincide with the beginning of a slot. Note that since the slot size is fixed in advance, arbitrary distributions of packet length cannot be accommodated by this protocol.

CSMA:

In this mode, it is required that a node is able to sense the presence of transmissions by its neighbors. A packet will be transmitted by a node only if that node is not already transmitting and no transmissions from its neighbors are sensed. Among the various CSMA protocols known, the minislotted version of CSMA considers the time axis to be divided into equally sized minislots. The size of a minislot is equal to the maximum propagation delay between pairs of neighboring nodes in the network. Transmissions are only allowed at the beginning of a minislot.

BTMA:

We assume the existence of a separate channel for the busy tone. As in CSMA

nodes must be able to sense carrier due to packet transmissions from their neighbors. In addition nodes are required to be able to sense the busy tone on the busy tone channel. As in CSMA, it is assumed that the time axis is minislotted, and that all users begin transmitting only at the beginning of a minislot. Several variants of BTMA exist depending on which set of nodes transmit the busy tone in any given situation as outlined below:

a. Conservative BTMA (C-BTMA):

Whenever a node senses a transmission, it emits a busy tone regardless of whether it is the immediate destination or not. Then any node that wishes to transmit is allowed to do so only if it is not already transmitting, no transmissions from its neighbors are sensed and no busy tone is sensed. In this scheme all nodes in the set $N^2(i)$ are inhibited from transmitting by the busy tone. Note that if the propagation delay between nodes is zero, then C-BTMA is collision free.

b. Idealistic BTMA (I-BTMA):

This scheme is similar to C-BTMA except that whenever a node senses a transmission it emits a busy tone only if it is the immediate destination. Without prior knowledge a node may not know if a particular transmission is destined to it or not, hence the name idealistic. It is considered here for comparison purposes.

We now examine in more detail some of the ramifications of these two BTMA schemes. Consider the transmission of a packet from node i to node j. In C-BTMA all nodes in the set $N^2(i)$ are blocked, while in I-BTMA only the nodes in the set $N(j)$ are blocked. As a consequence, under C-BTMA certain transmissions may be unnecessarily blocked, while under I-BTMA these transmissions may take place successfully without interfering with j's reception. To illustrate this point, we consider the following situation as depicted in figure 2. Let node i be transmitting to node j (which we denote by $< i,j >$), and let all other nodes be silent. Assume that a packet from node $k \in N^2(i) - [N(i) \bigcup N(j)]$ destined to node $m \notin N(i)$ is scheduled for transmission

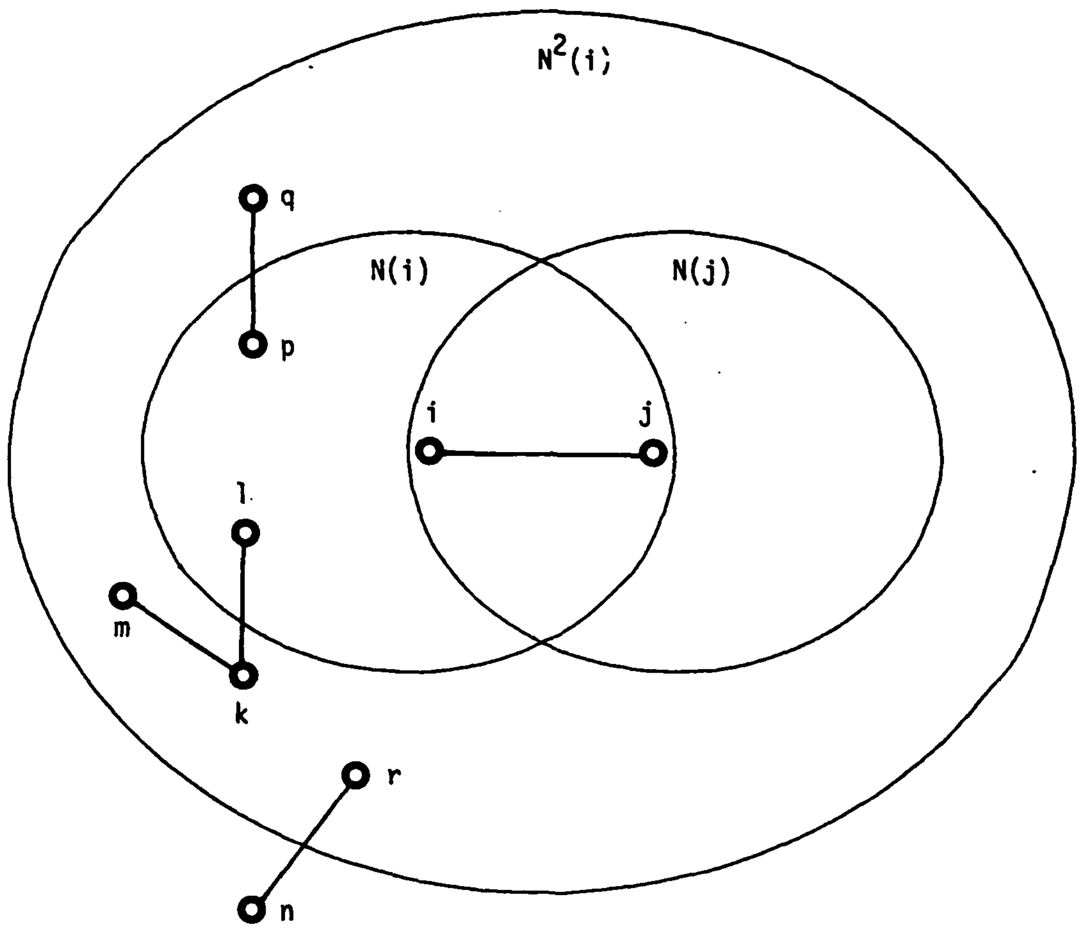

Fig. 2: Example of a set of packet transmissions under BTMA protocols.

during the transmission $< i, j >$. In C-BTMA the transmission $< k, m >$ is blocked, while in I-BTMA it results in a successful transmission.

On the other hand, in I-BTMA it is possible to allow a transmission to take place that will be unsuccessful, and whose presence may block a number of other potentially successful transmissions; in C-BTMA such a transmission is inhibited by the protocol, allowing the potentially successful transmissions to then take place. For example, referring to figure 2, consider now that a packet from node k destined to node $l \in N(i)$ is scheduled for transmission during the transmission time of $< i, j >$. Furthermore, let $n \notin N^2(i)$ and $r \notin N(i)$, and a consider a transmission $< n, r >$ to be scheduled at some point in time within one packet transmission time of the scheduled transmisson $< k, l >$. In I-BTMA, the transmission $< k, l >$ is not blocked, but is unsuccessful; the transmission $< n, r >$ is blocked if $n \in N(k)$; the transmission $< n, r >$ is unblocked but unsuccessful if $n \notin N(k)$ and $r \in N(k)$. In the latter case n's unsuccessful transmission will have blocking and interfering effects on its neighbors similar to those of node k's transmission. In C-BTMA, the transmission $< k, l >$ is blocked and the transmission $< n, r >$ is successful.

c. Hybrid BTMA (H-BTMA):

In I-BTMA we assume hypothetically that as soon as a node receives a packet it knows immediately whether or not that packet was destined for it. In practice this information is obtained from the packet header. Assuming that the packet header is processed as soon as it is received and before the entire packet is received, the time at which a node can determine whether or not it is the intended immediate destination for a particular packet reception is at the end of the processing of the packet header. In H-BTMA, a node operates as in C-BTMA until the header is processed, upon which time it operates as in I-BTMA. Alternatively one may conceive of a scheme in which the node operates as in CSMA until the header is processed prior to switching to I-BTMA. We consider only the former scheme in this study.

d. Improved Idealistic BTMA (II-BTMA):

As discussed above, depending on the particular situation, both C-BTMA and I-BTMA have their shortcomings. In order to see how good a performance is achievable using random multiaccess protocols in multihop packet radio networks, we consider the following hypothetical II-BTMA protocol: As in I-BTMA, only the immediate destination emits a busy tone. Then, if a node wants to transmit, it is allowed to do so only if it is not already transmitting, it is not already receiving a packet destined to it, no busy tone is sensed, and its immediate receiver is not currently sensing carrier.

The essence of II-BTMA is that given the state of the network in terms of ongoing transmissions, a scheduled transmission in the network is allowed to take place if it has a high probability of not interfering with an ongoing transmission; futhermore, once allowed, the transmission has a high probability of success.

The implementation of this protocol may be difficult and expensive, given all the information needed to determine the right of transmission. However with enough resources, the implementation can be made feasible. For example one possibility is the use of a busy tone emitted by a node when it is receiving a packet destined to it, and the use of a carrier sense tone emitted by a node when it is detecting carrier due to a packet transmission not destined to it; furthermore it is required that the carrier sense tone be coded so that it allows unique identification of the node emitting it.

To illustrate the benefits gained by this scheme, we reexamine the various situations considered above and depicted in figure 2. Let nodes i, j, k, l, m, n and r, and the scheduled transmissions among them be as defined above. Transmission $< k, l >$ is inhibited due to l's carrier sense tone, and transmission $< n, r >$ can take place successfully. On the other hand, transmission $< k, m >$ can take place successfully; as for transmission $< n, r >$, it is inhibited if $r \in N(k)$, but is successful if $r \notin N(k)$. Moreover, given an on-going transmission from node i to node j, and all other nodes silent, any node $p \in N(i) - N(j)$ with a packet scheduled for transmission to a node $q \notin N(i)$, during the transmission $< i, j >$, will transmit successfully in II-BTMA while

the node is blocked in both C-BTMA and I-BTMA (as well as CSMA). Thus the action taken in II-BTMA and the resulting outcome in each situation is expected to lead to a performance that is superior to that of both I-BTMA and C-BTMA.

CDMA-ALOHA:

This protocol is implemented by means of the spread spectrum technique. Each node is assigned a unique code for reception. Nodes wishing to transmit to a particular node must use the code assigned to that node. A receiver that is idle 'locks onto' a packet with the appropriate code by correctly receiving a preamble appended in front of the transmitted packet. We assume that preambles are of infinitely short duration and that the presence of any number of overlapping transmissions on the channel does not affect the captured packet's reception. (Thus perfect capture is assumed). When reception of a packet is completed the receiver becomes free again until another packet with the correct preamble is received. With these conditions a node is allowed to transmit only if it is neither transmitting nor receiving.

4. The Simulation Model and the Measures of System Performance.

In this section we describe the constituent variables of packet radio networks that are included in the simulation model, namely the topology, routing, flow control and nodal storage capacity. We also describe the traffic model used for packet generation, the packet scheduling alogorithms, and the performance measures used in evaluating the access schemes. For a discussion of the implementation of the simulation model, the validation of the software and the estimation of the performance statistics, refer to Appendix 1.

It should be kept in mind that our primary aim is to investigate the performance of the channel access policy. Many of the choices below are made for simplicity so as not to distract from this goal, and they are identical for each access scheme. That is not to say that the simulator is restricted to these choices; on the contrary, it is designed so as to allow a wide range of choices to be easily implementable.

4.1 Essential Variables in Packet Radio Networks.

a. Topology:

We assume there exists a population of N nodes distributed over some geographical area. The connectivity of the network is specified by a hearing matrix, i.e., a $N \times N$ matrix in which the (i,j)'th element will be 1 if node i hears node j and zero otherwise.

The nature of electromagnetic propagation implies that there will be a delay between the time that a packet is transmitted, and the time it is received. The value of the delay depends on the geographical separation between pairs of nodes and could be different for every pair of nodes. For the sake of simplicity it is assumed that the same propagation delay exists between all pairs of nodes.

b. Routing:

Since the network utilizes store-and-forward operation it is necessary to specify a routing function which determines the next node in the chain of nodes from source to destination. It is often given in the form of a routing matrix, in which the (i,j)'th element is the immediate destination node for a packet currently at node i and ultimately destined for node j. If the elements of the matrix are fixed, the routing is called static. If the elements are allowed to change, the routing is called dynamic or adaptive [8]. In this study a static routing scheme based on a minimum number of hops is employed.

c. Nodal Storage Capacity, Flow Control and Acknowledgements:

Each node has a finite number of buffers associated with it. A packet contained in a buffer may be newly generated by a user at that node, or in transit (i.e., successfully received over the channel and in transit to its destination). The order in which packets at a node are serviced (i.e., transmitted) is first come, first served (FCFS).

If the level of offered traffic input by the users exceeds the 'capacity' of the network, congestion will occur resulting in poor efficiency and long delays . One extreme form of congestion is deadlock, in which no data packets get through to their

destinations and the network effectively breaks down. The simplest example of deadlock occurs when two nodes A and B, directly connected, both have full buffers with the head of A's queue destined to B and the head of B's queue destined to A. With the FCFS service discipline, neither A nor B is able to forward the head of the queue and a deadlock occurs. The purpose of flow control is to prevent congestion and deadlocks by regulating the buffer allocation and offered traffic pattern. A survey of flow control schemes can be found in [9]. The approach taken here is based on limiting the input of newly generated traffic into the network when the load increases. In particular the buffer space at a node is partitioned into two sections, with the top section (including the head of the queue) available to both types of incoming packets (newly generated and in transit), and the tail section reserved only for transit packets. Newly generated packets which find the top section entirely occupied are lost.

Due to the possibility of collisions at each hop, it is desirable to have some type of hop-by-hop acknowledgement, transmitted by the immediate destination to indicate the successful reception of a packet [18]. In this study we assume that acknowledgements are instantaneous, that is, the sender learns of the success or failure of its transmission as soon as the packet has been completely received at the intended immediate destination. In addition the acquisition of this knowledge is assumed not to require any communication bandwidth.

4.2 Traffic Model:

We define an input traffic pattern by the matrix $[\gamma_{ij}]$, such that γ_{ij} is the average number of packets per unit time offered at node i ultimately destined for j. The generation of packets at a source node forms a random process considered here to be Poisson. Packets are assumed to be of constant length.

4.3 Scheduling of Packet Transmissions:

Associated with each node is a queue of packets (possibly empty) to be transmitted over the channel. When the queue is nonempty, the node waits until the next scheduled point in time (defined here recursively), whereupon it schedules the transmission of the

head of the queue. Clearly actual transmission may or may not take place depending on the particular protocol in use. As previously indicated in section 3, if the transmission is inhibited, or if it is unsuccessful, then the packet is rescheduled for transmission after a random rescheduling delay. This rescheduling delay is chosen to be exponentially distributed with mean $1/\nu$ units of time for ALOHA and CDMA, geometrically distributed with mean $1/\sigma$ packet slots for slotted ALOHA, and geometrically distributed with mean $1/p$ minislots for CSMA and BTMA. If at the scheduled point in time, the transmission takes place successfully, then the packet is deleted from the head of the queue, and the transmitter node selects a new point in time at which it will service the new head of the queue.

When a packet arrives at a node which is non-empty, it is enqueued. If upon arrival the queue is found empty, the packet is scheduled for immediate transmission.

4.4 Measures of System Performance.

There are essentially two measures of performance which we consider in our evaluation of channel access schemes, namely packet delay and system throughput [15]. We define the delay matrix so that its (i,j)'th element δ_{ij} specifies the average time a packet from node i destined to node j spends in the system from the time it originates from the source until it is finally successfully received at the ultimate destination. The average packet delay over the entire network is given by

$$T = \sum_{i=1}^{N} \sum_{j=1}^{N} \frac{\gamma_{ij}}{\gamma} \delta_{ij}$$

where γ represents the total offered traffic and is given by

$$\gamma = \sum_{i=1}^{N} \sum_{j=1}^{N} \gamma_{ij}.$$

We also define the throughput matrix $[S_{ij}]$ so that its (i,j)' th element S_{ij} is the average number of successful receptions at destination node j of packets that originated

at source node i per packet transmission time. The total network throughput is

$$S = \sum_{i=1}^{N} \sum_{j=1}^{N} S_{ij}.$$

So, in this study, γ is the input parameter, and S and T are the performance measures.

5. A Numerical Example: A Six Node Ring

A simple topology with a relatively small number of nodes which exhibits the hidden node problem is desired. While a chain is one of the simplest such topologies, it lacks uniformity in traffic flow due to edge effects. Therefore a ring with six nodes is chosen. Each node generates Poisson traffic at rate $\gamma/6$. The input traffic at a node is destined uniformly to all other nodes in the ring so that each node in the network is statistically identical with respect to traffic flow. Fixed routing is employed with the additional rule that in the event of a tie traffic is sent clockwise. Each node is allocated a buffer size of thirteen. The top section of the buffer (refer to section 4.1c) consists of a single packet buffer and the remaining twelve are reserved for transit packets. The unit of time in the simulation is taken to be the (constant) propagation delay. The packet size is assumed fixed and set to 100 units. This is based on assuming a signaling rate of 100kbits/s, a packet size of 1000 bits and a distance between neighbors of 20 miles (typical values obtained from [18]). The ratio of propagation delay to packet transmission time, denoted by a, is in this case equal to 0.01.

For each protocol we examine two performance curves: throughput versus input traffic rate and delay versus throughput. In both cases a different curve results for each value of the retransmission parameter. An outer profile design curve is obtained by taking the outer profile of a family of such curves. From these design curves we can obtain the maximum throughput obtainable for a particular traffic rate, and the minimum average packet delay for a given throughput. In the absence of an analytic model there is no straightforward way to obtain optimum retransmission probabilities. In all the results that follow, we employed experimental design methods, based on the

tradeoff between the number of collisions incurred, and the idle time wasted in the presence of work outstanding. Indeed, too small a value of average rescheduling delay may cause a large number of collisions, while too large a value leads to long idle periods. Thus, for each value of the traffic rate γ, it is expected that there exists a single value for the average rescheduling delay which leads to maximum throughput and minimum delay. Evidence for this hypothesis is given by previous analysis of single hop networks and by the numerical results derived from the simulation.

In the curves discussed below, the traffic rate is measured in units of packets per node per transmission time, i.e. γ/N. Also note that the throughput measure used in these curves is s, the average number of successful transmissions per node per packet transmission time. Denoting by $\overline{n}$ the average path length from source to destination, s is related to the total network throughput by

$$s = \overline{n}S/N = 1.8S/6 = 0.3S.$$

The delay is measured in units of packet transmission time.

In figures 3 and 4 we plot s versus γ/N and T versus s respectively for the ALOHA scheme. The maximum throughput obtainable is approximately 0.078, achieved at a delay of 14. This compares very well with the maximum throughput of 0.08 predicted in [5]. Also shown in Figure 3 is the flattening out of the throughput curve at high traffic rates, due to the flow control mechanism becoming active and regulating the amount of traffic entering the network. An increasing fraction of packets at these higher rates is lost. Note that the minimum average packet delay at zero load is precisely $\overline{n} = 1.8$. In figures 5 and 6 we plot similar curves for slotted ALOHA. We see that the maximum throughput obtainable is approximately 0.14, at a delay of 22. This increase in throughput over pure ALOHA (by a factor of 1.8) is to be expected since slotting the system decreases the fraction of time spent in collisions (an effect similar to that observed in single hop systems). Slotting also causes the minimum average packet delay at zero load to be increased by half a slot over ALOHA to 2.3. In figures 7 and 8 we plot the corresponding curves for CSMA. The maximum

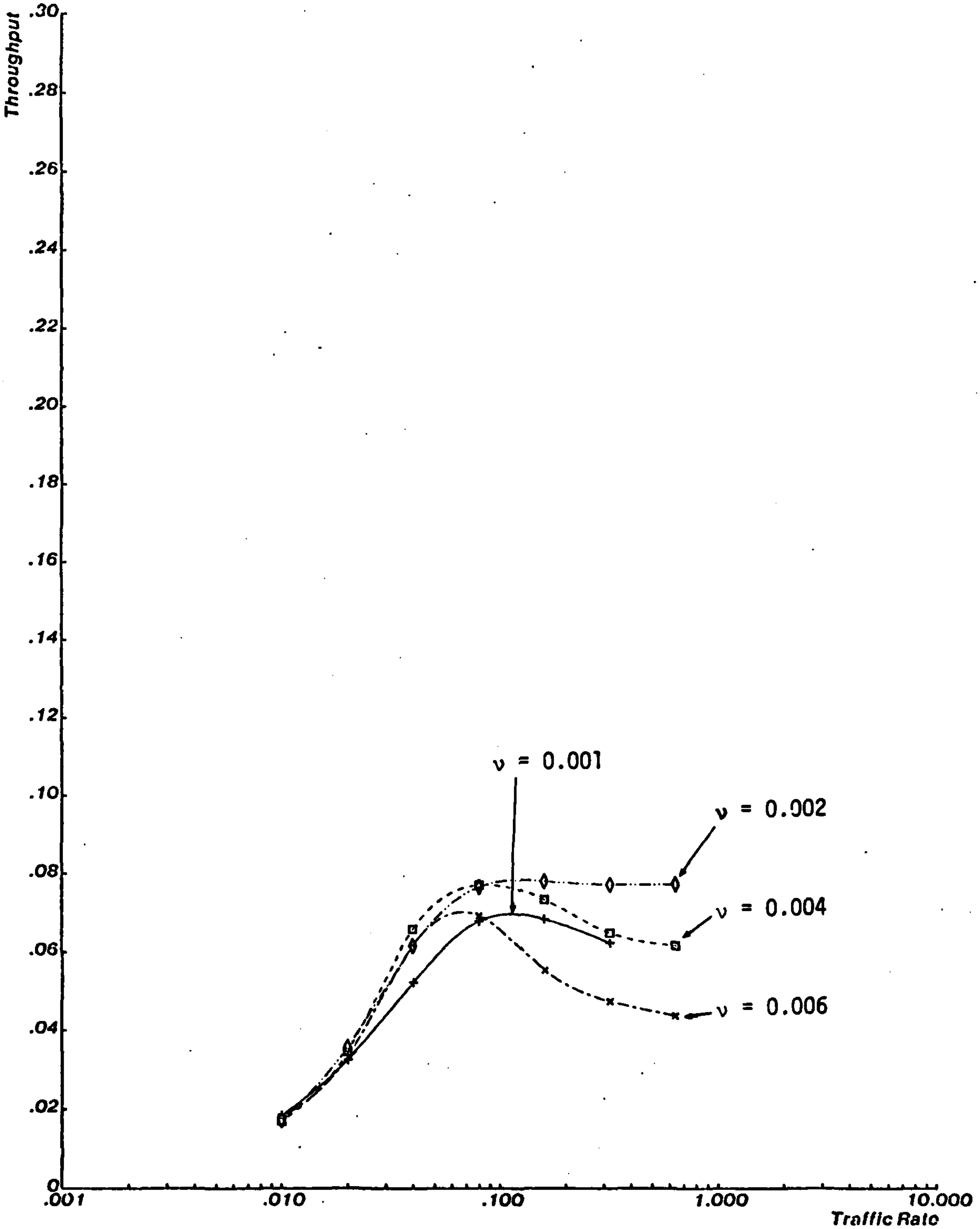

Fig. 3: Throughput versus input traffic rate for ALOHA for different values of ν.

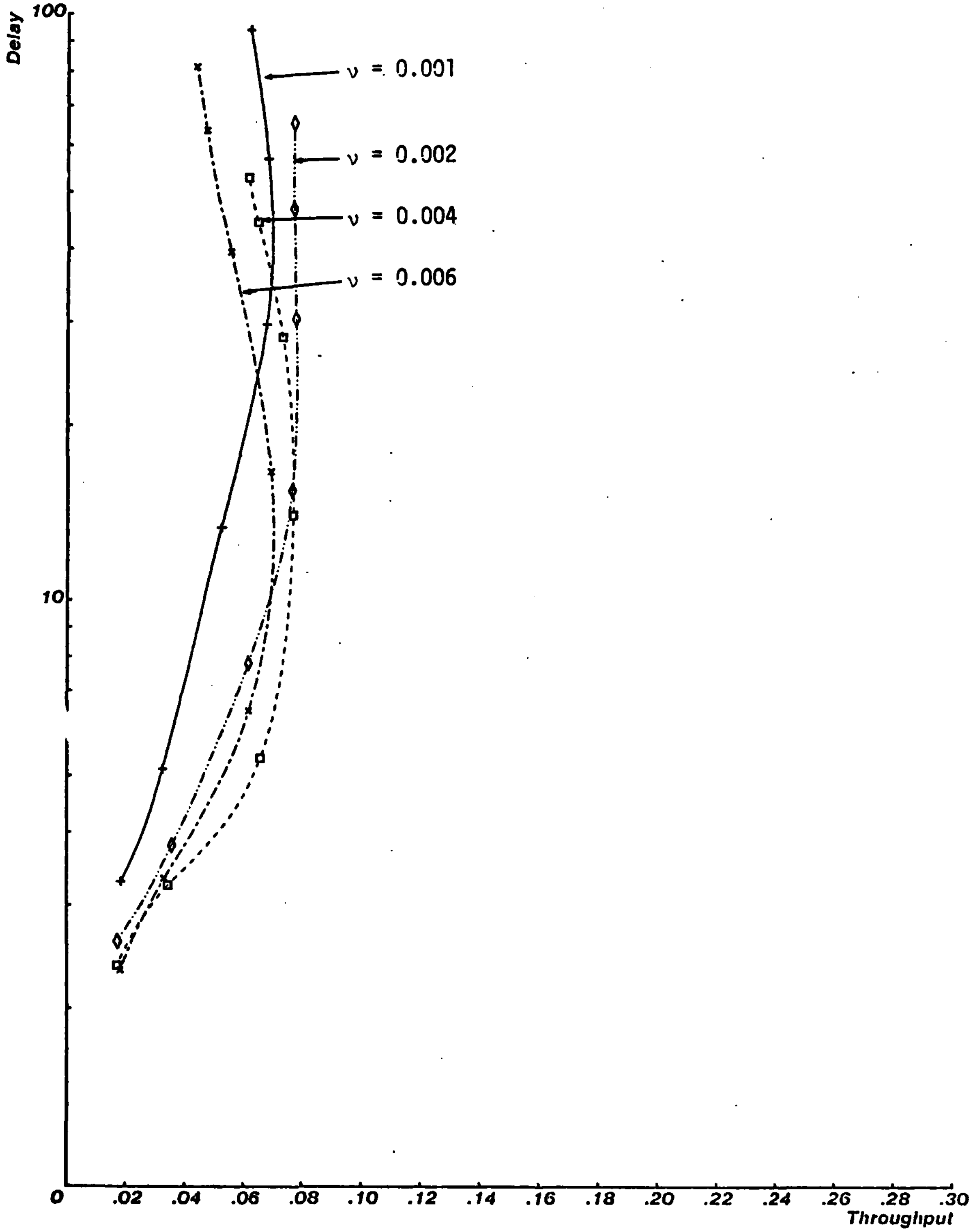

Fig. 4: Delay versus throughput for ALOHA for different values of ν.

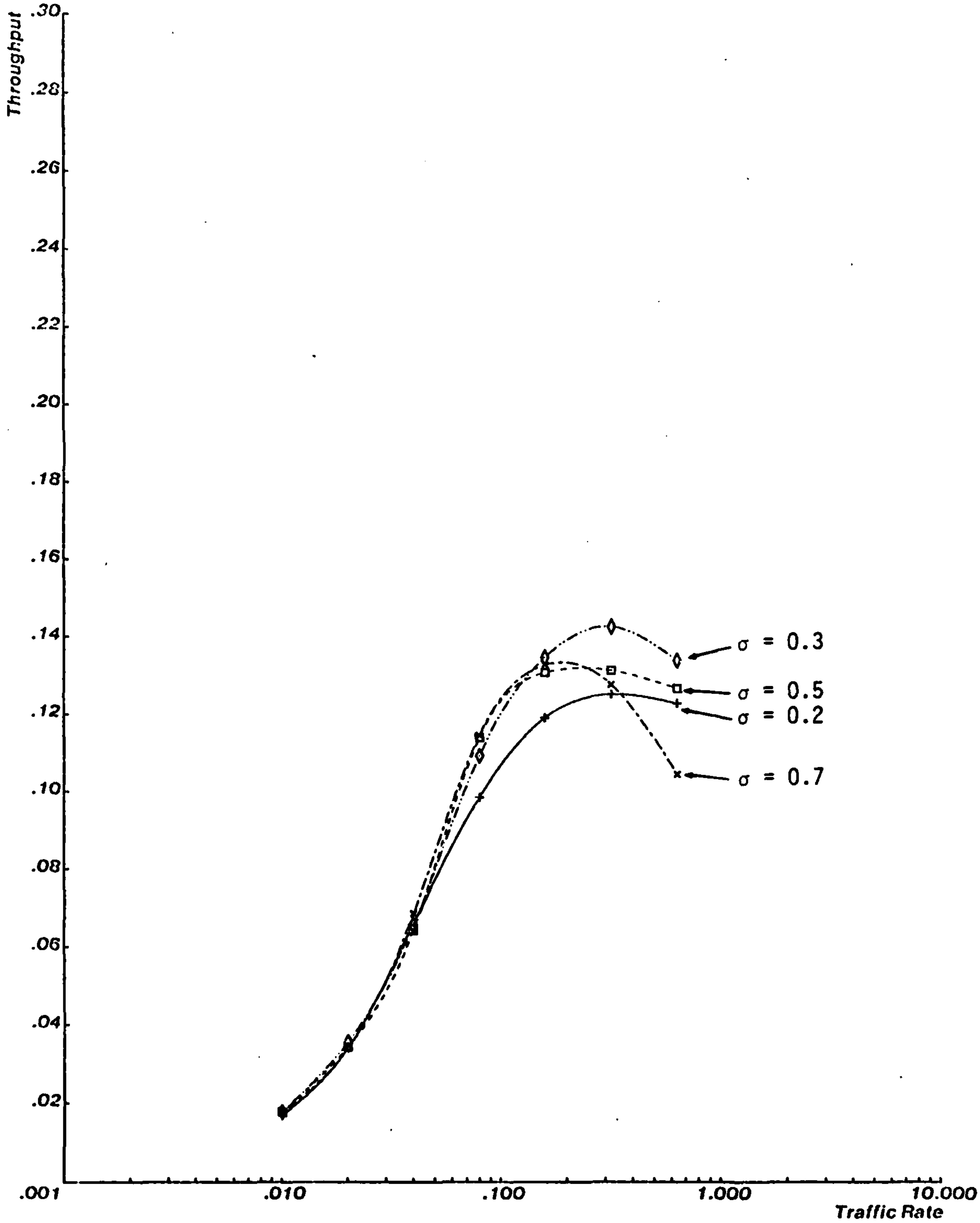

Fig. 5: Throughput versus input traffic rate for Slotted ALOHA for different values of σ.

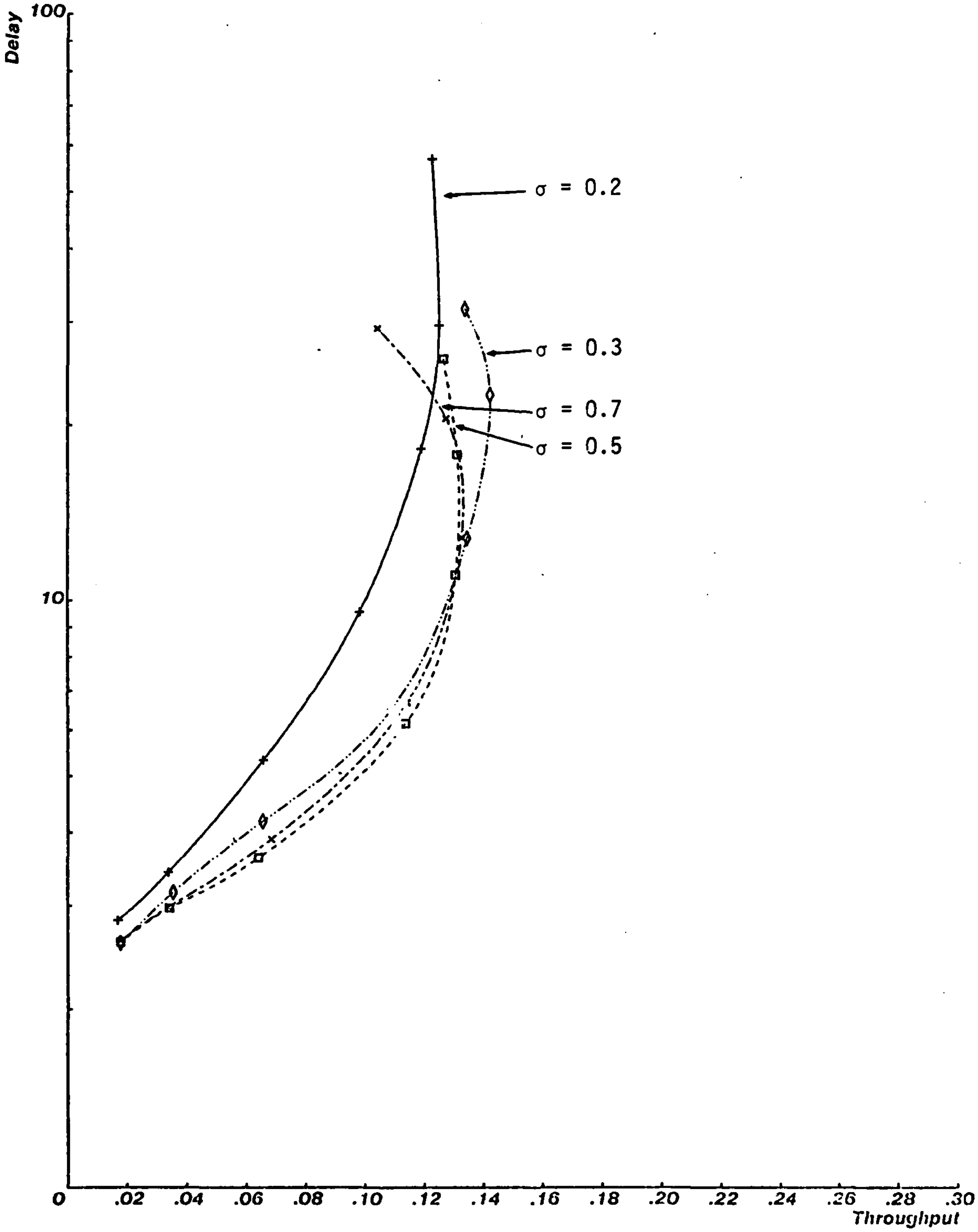

Fig. 6: Delay versus throughput for Slotted ALOHA for different values of σ.

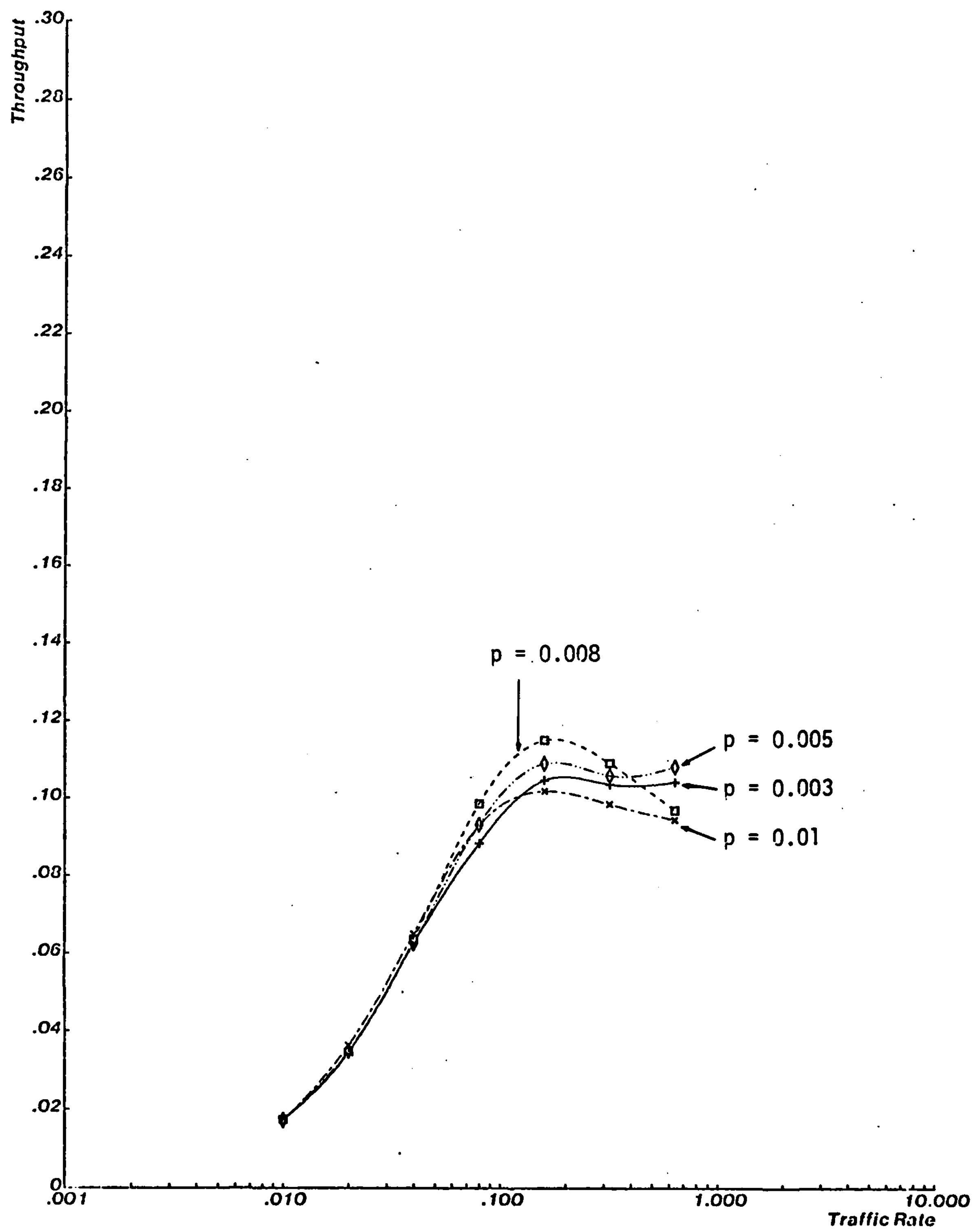

Fig. 7: Throughput versus input traffic rate for CSMA for different values of p.

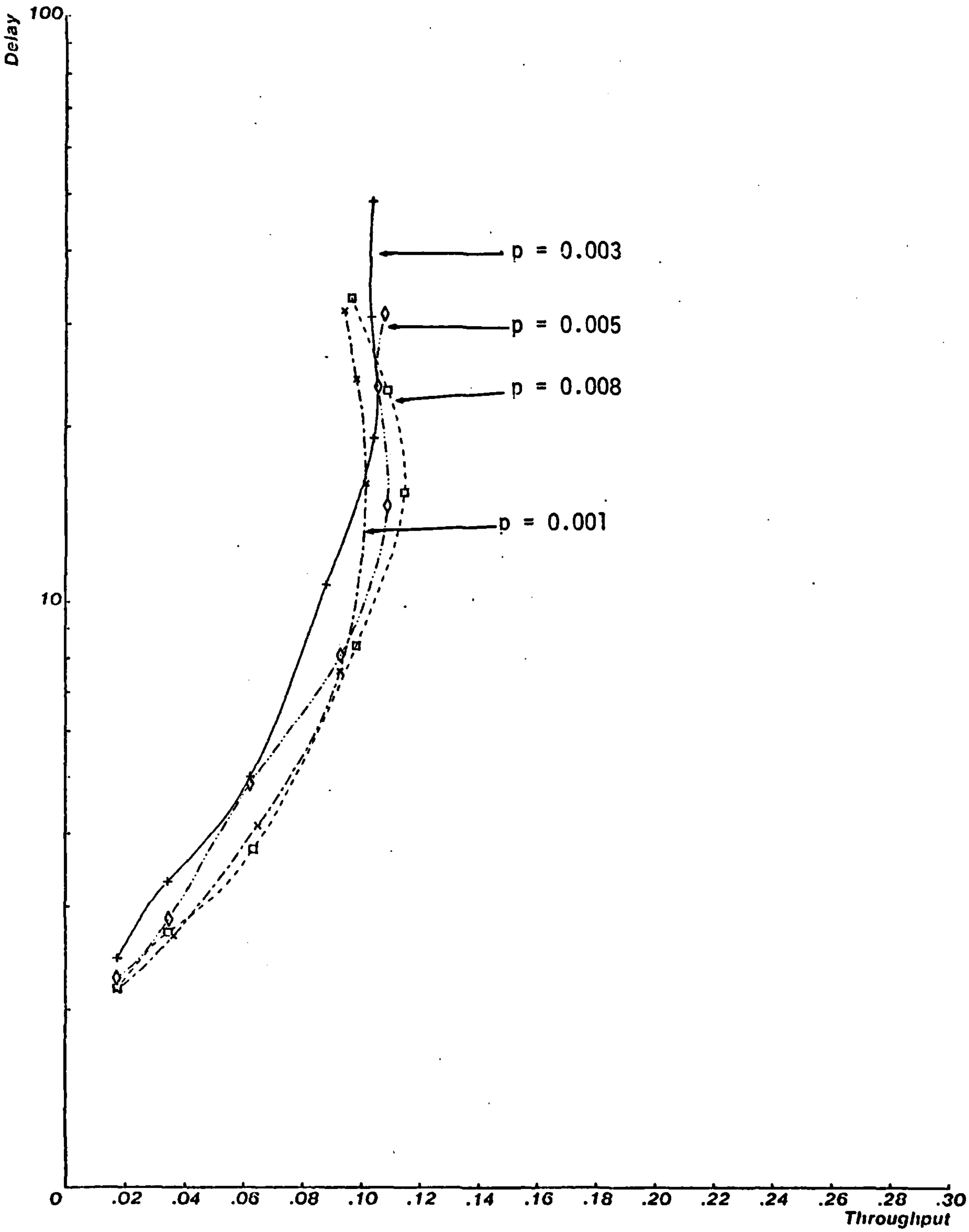

Fig. 8: Delay versus throughput for CSMA for different values of p.

throughput is about 0.11, which is less than that of slotted ALOHA, achieved at a delay of 15. These results may be contrasted with those in fully connected, single-hop environments where CSMA outperforms slotted ALOHA [13]. Here we are seeing the effect of collisions due to the presence of hidden nodes, leading to a degradation in the performance of CSMA. Figures 9 and 10 give corresponding results for C-BTMA and show an achievable throughput of at least 0.26 at a delay of 11, which is a significant improvement over the previous results. We should note that under the conditions of zero capture and zero propagation delay the maximum throughput under perfect scheduling is one third. Under these conditions, it has been shown in [5] that C-BTMA achieves this maximum for this topology. This is due to the nature of the topology and the collison free operation of C-BTMA when $a = 0$. Using C-BTMA with $a = 0.01$, we have approached within 20% of the theoretical limit. This decrease is caused in part by collisions due to $a \neq 0$. Figures 11 and 12 give the corresponding results for I-BTMA. They show a maximum throughput of about 0.22 at a delay of 9. This is better than CSMA and slotted ALOHA but not as good as C-BTMA. The decrease in throughput with respect to C-BTMA in this example is not unexpected (refer to the discussion in section 3). The results corresponding to H-BTMA are given in figures 13 and 14. We assume a header length equal to seven tenths of the packet length. H-BTMA exhibits performance between that of C-BTMA and I-BTMA. The maximum throughput is at least 0.24 at a delay of 10. The results corresponding to II-BTMA are plotted in Figures 15 and 16. We see that the throughput achievable under the II-BTMA scheme is about 0.3 (i.e., within 10% of that of perfect scheduling) at a delay of 10. This is because, as discussed previously, this protocol minimizes the blocking that takes place in the network while removing predictable sources of collisions. Its performance exceeds both that of C-BTMA and I-BTMA.

All the above results are summarized in Figures 17 and 18, by plotting on the same graph, the outer envelopes for all schemes discussed so far, allowing their comparison in this particular illustrative example.

We now consider CDMA-ALOHA. The results are plotted in figures 19 and 20

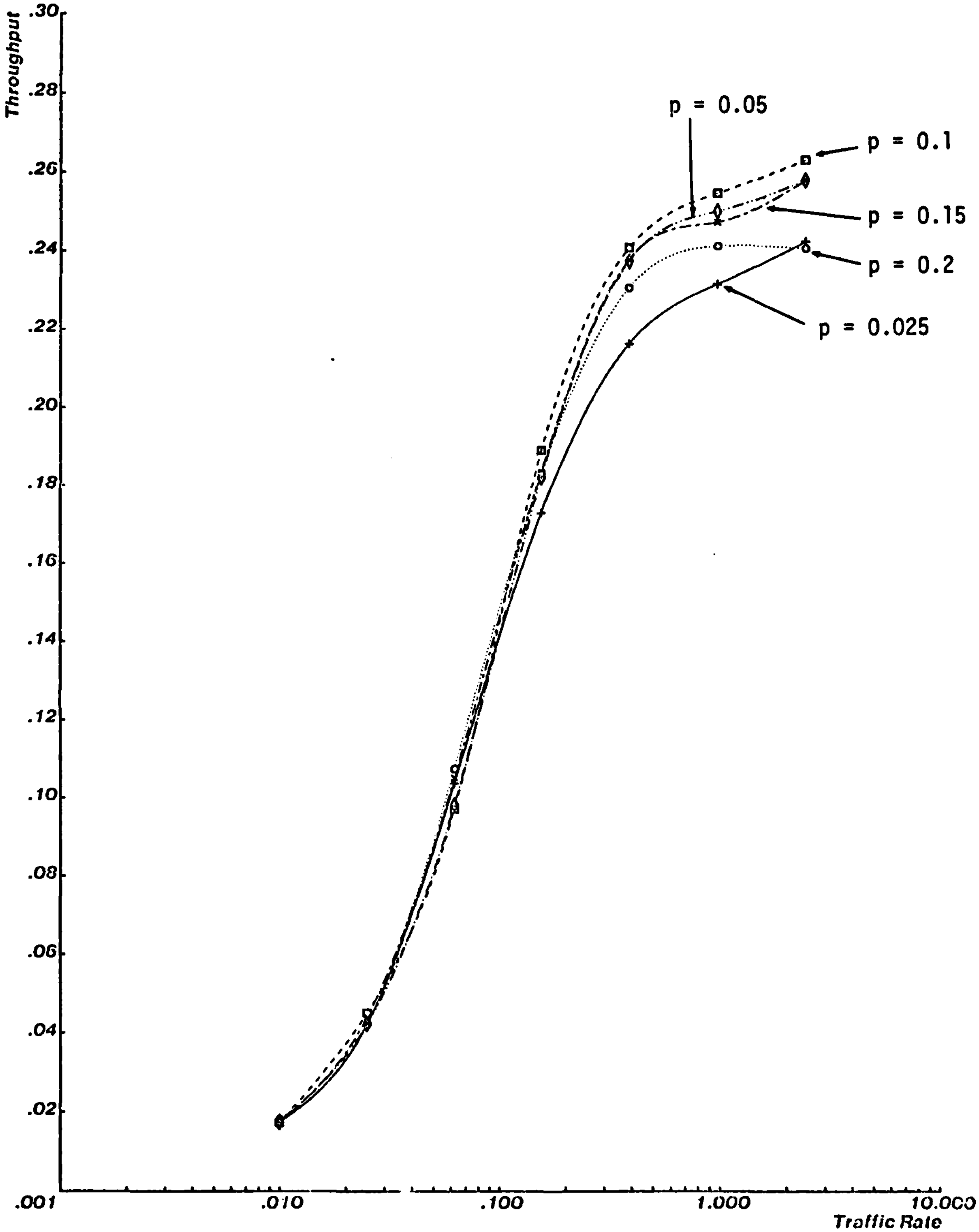

Fig. 9: Throughput versus input traffic rate for C-BTMA for different values of p.

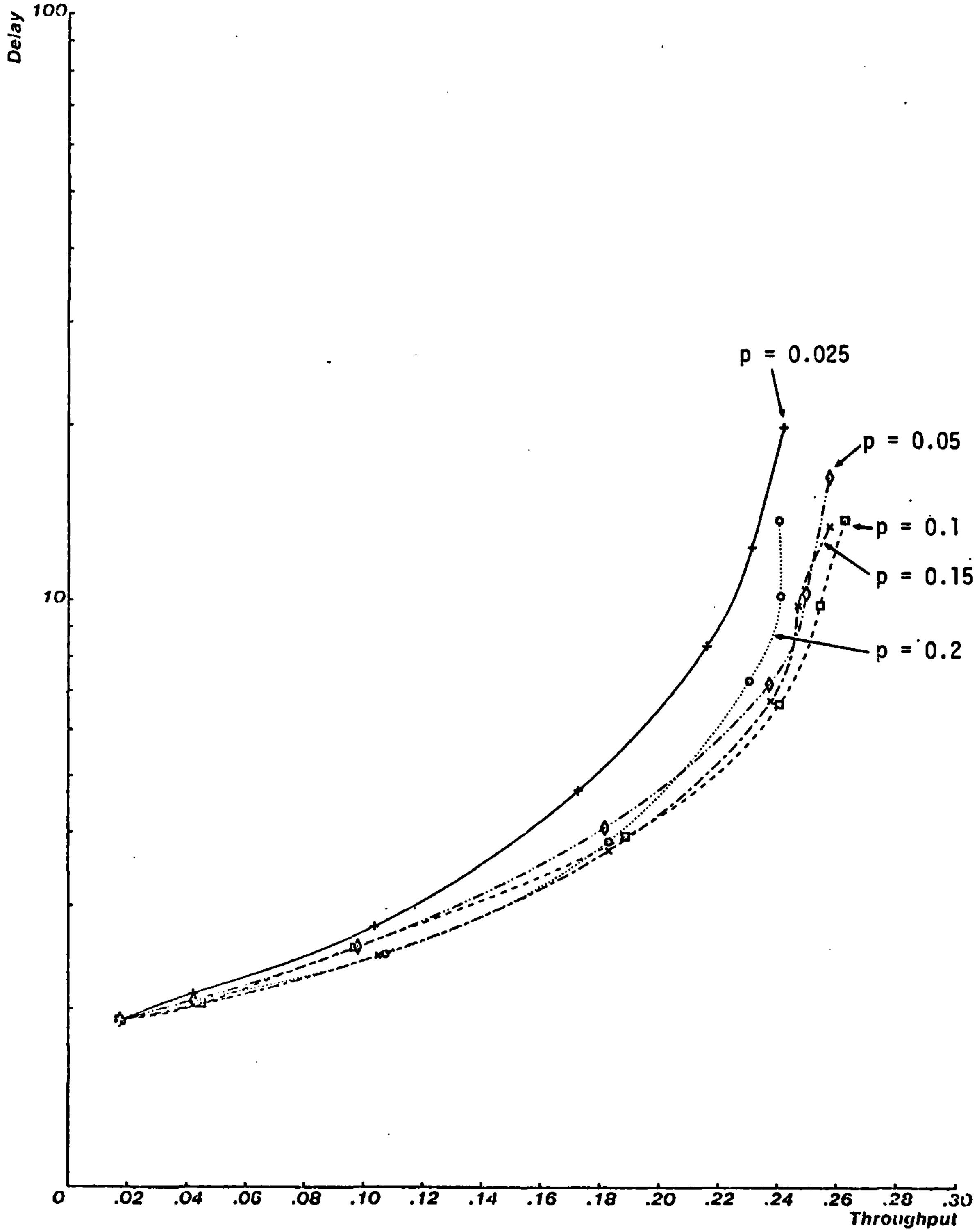

Fig. 10: Delay versus throughput for C-BTMA for different values of p.

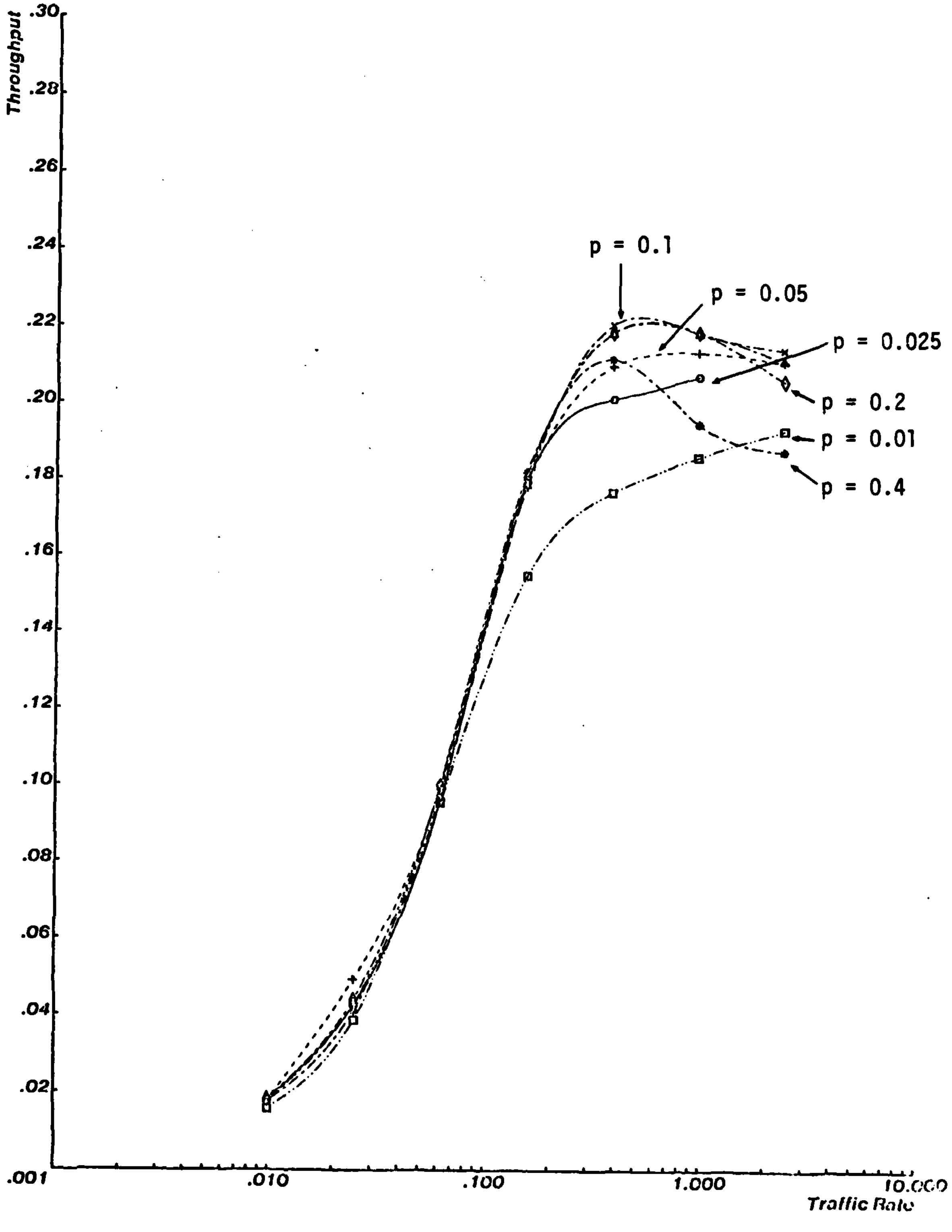

Fig. 11: Throughput versus input traffic rate for I-BTMA for different values of p.

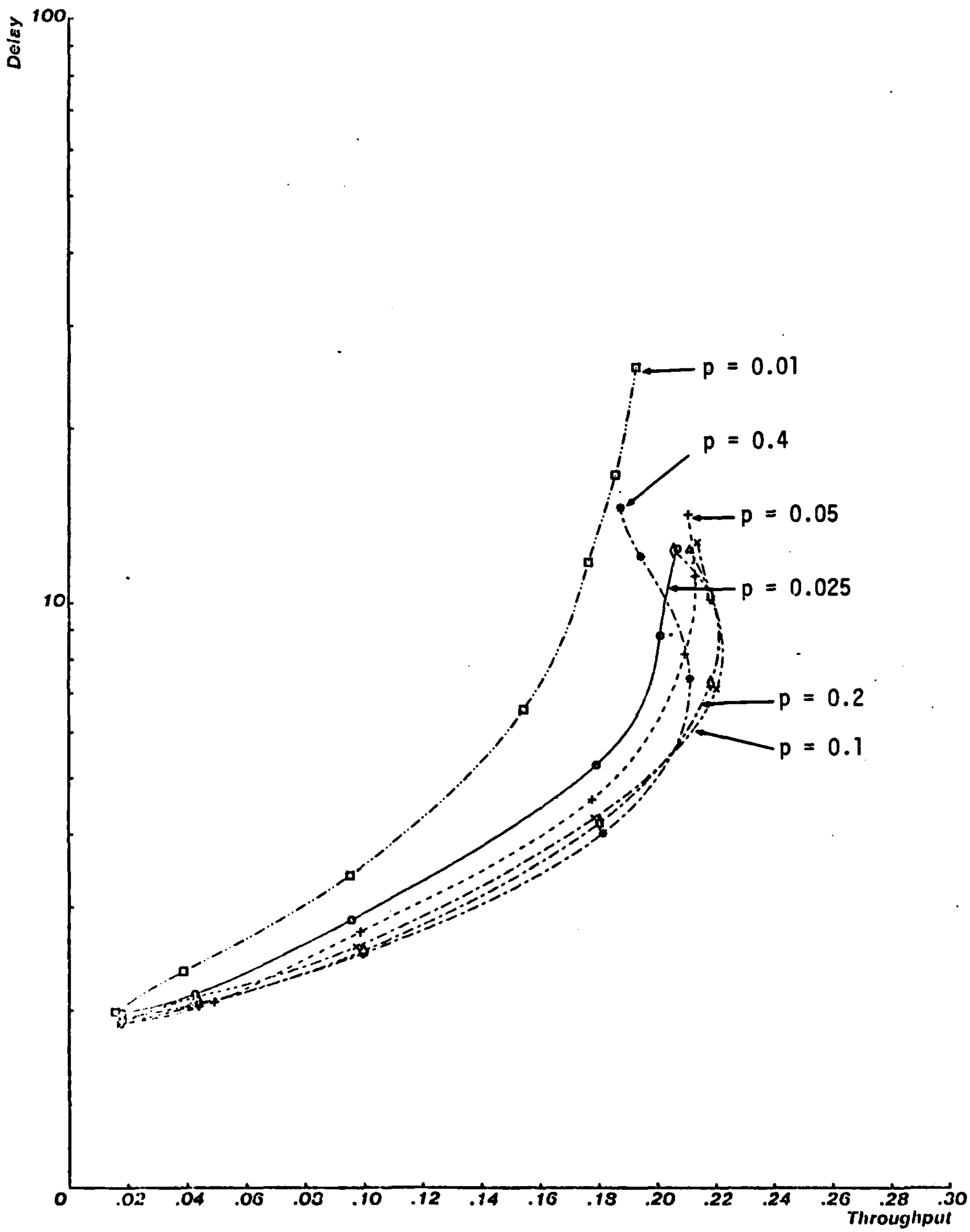

Fig. 12: Delay versus throughput for I-BTMA for different values of p.

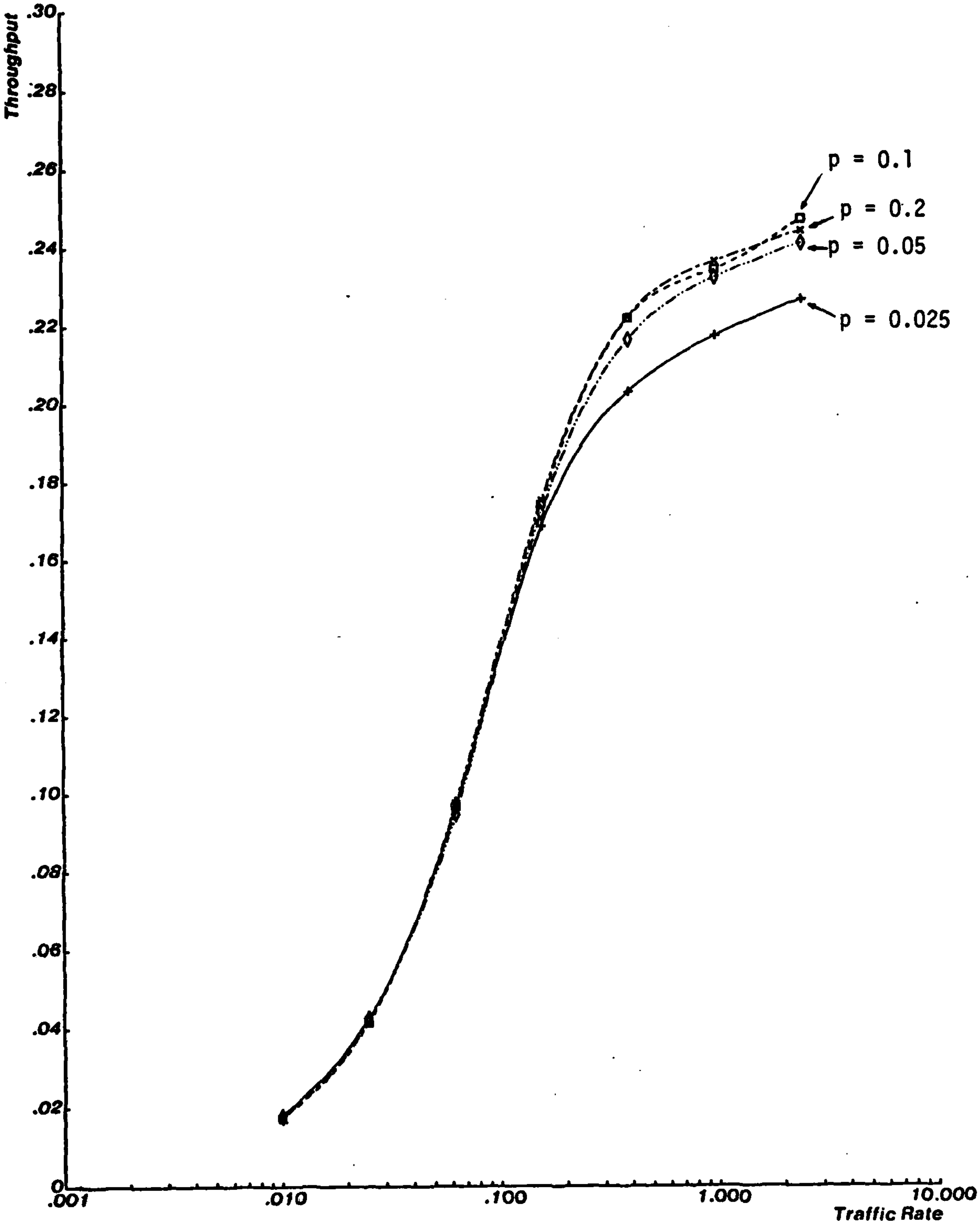

Fig. 13: Throughput versus input traffic rate for H-BTMA for different values of p.

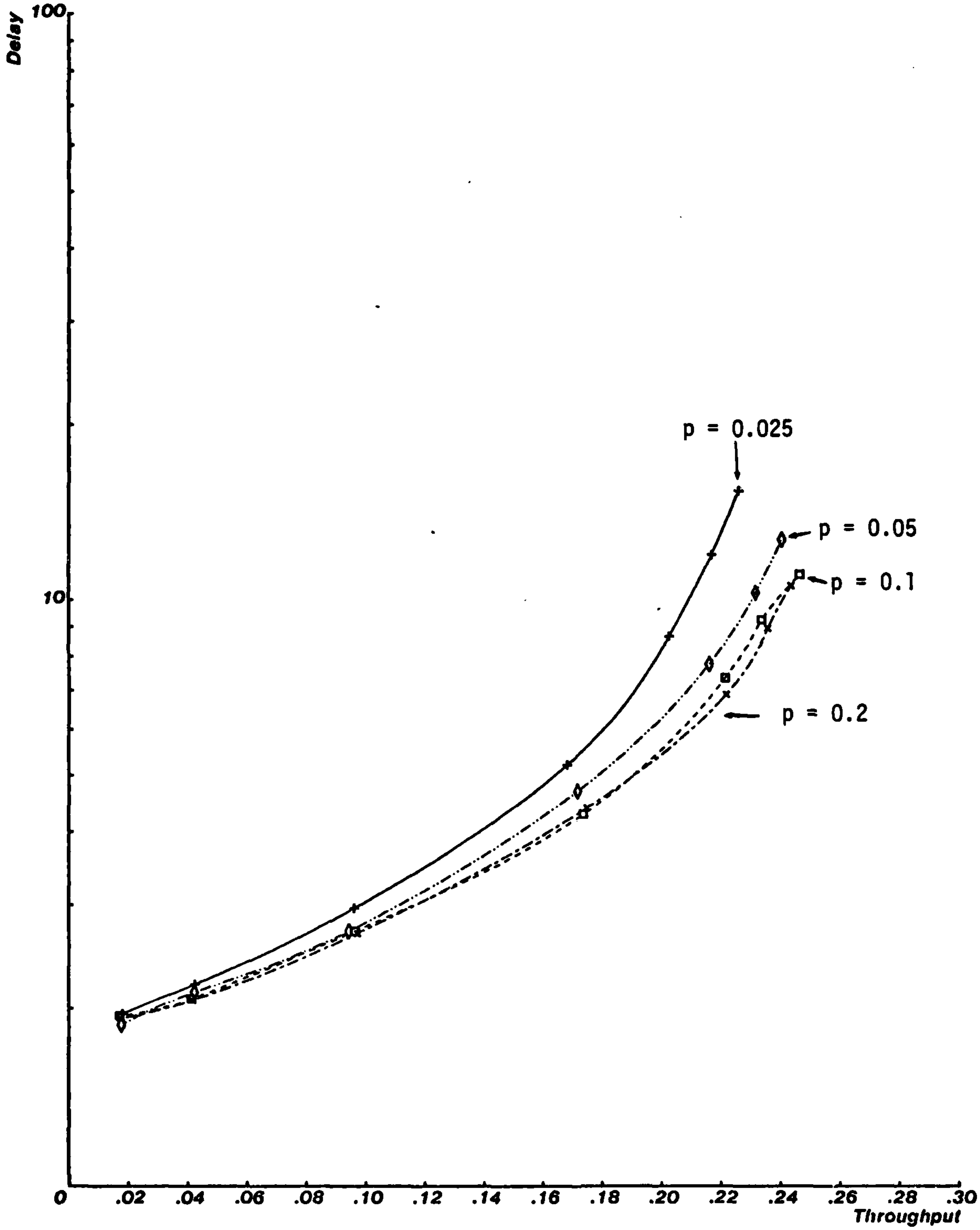

Fig. 14: Delay versus throughput for H-BTMA for different values of p.

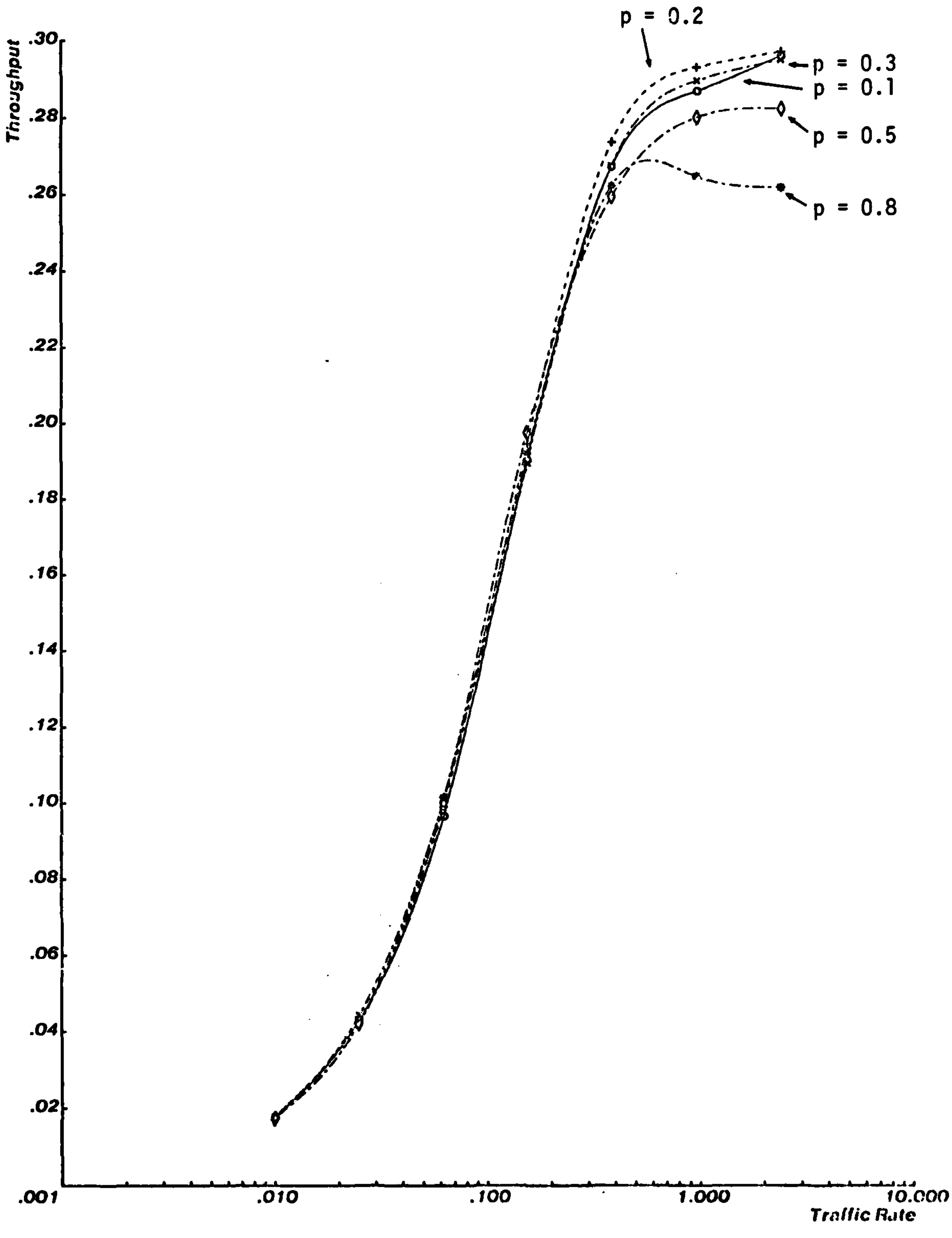

Fig. 15: Throughput versus input traffic rate for II-BTMA for different values of p.

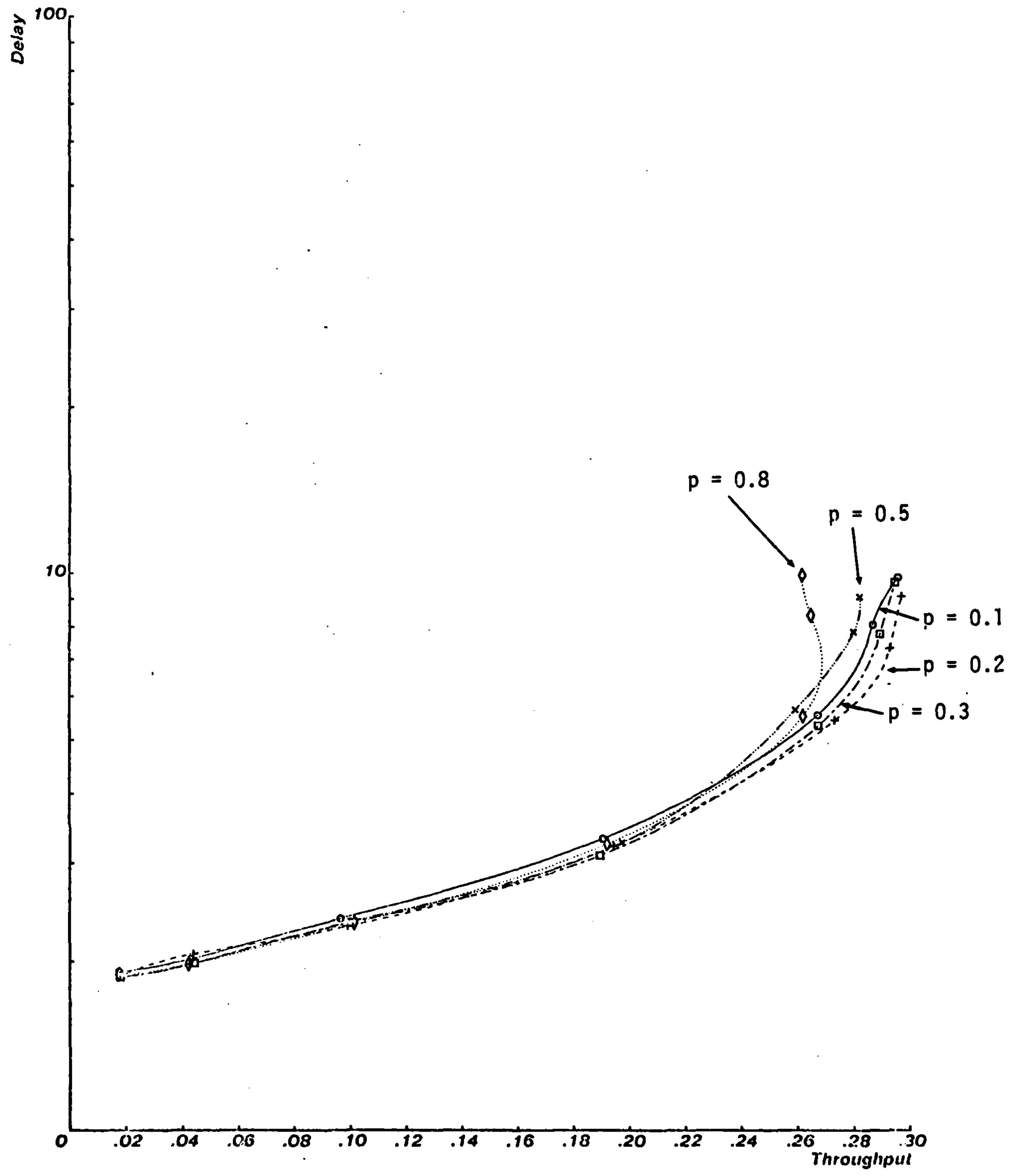

Fig. 16: Delay versus throughput for II-BTMA for different values of p.

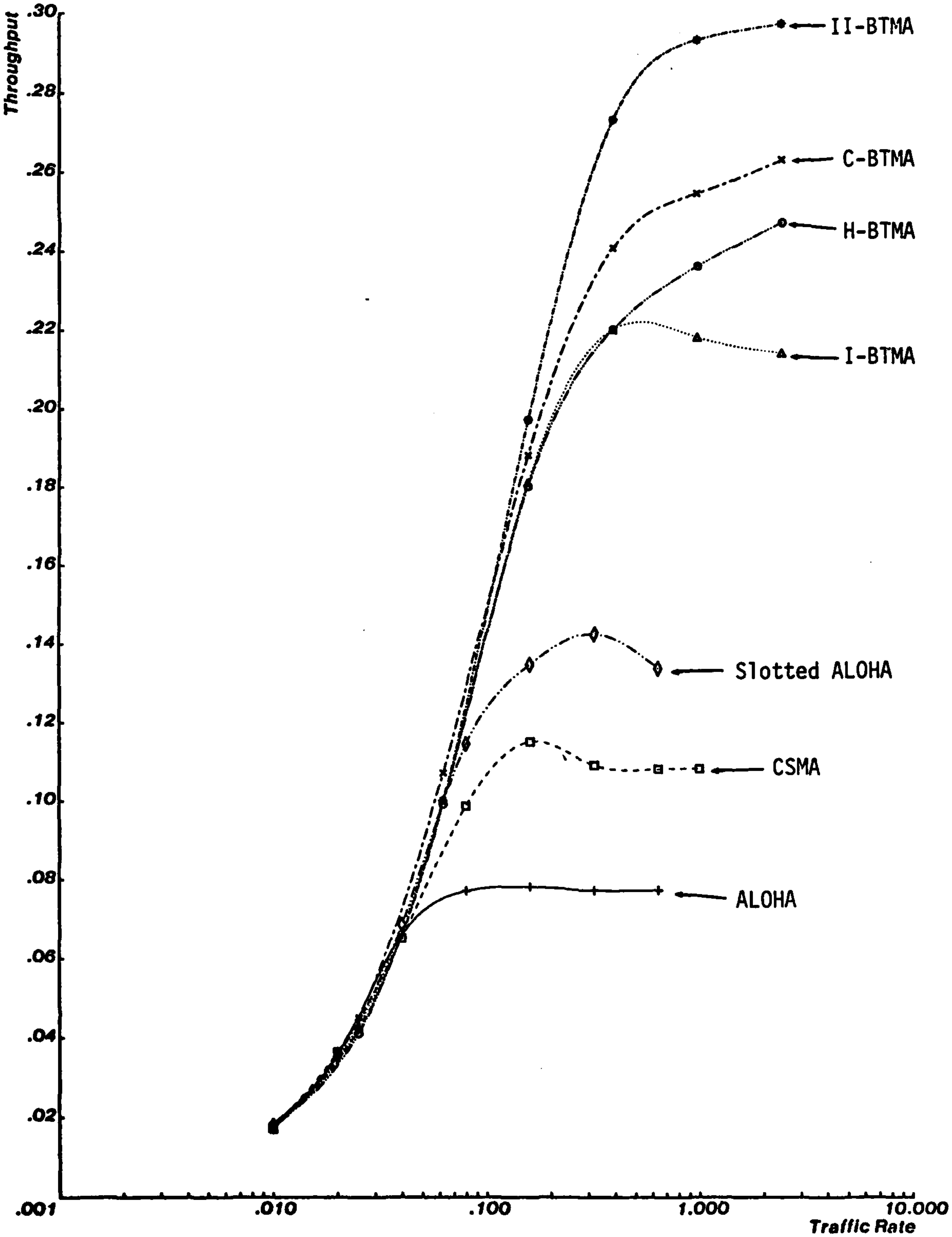

Fig. 17: Envelope of throughput versus input traffic rate for the different schemes.

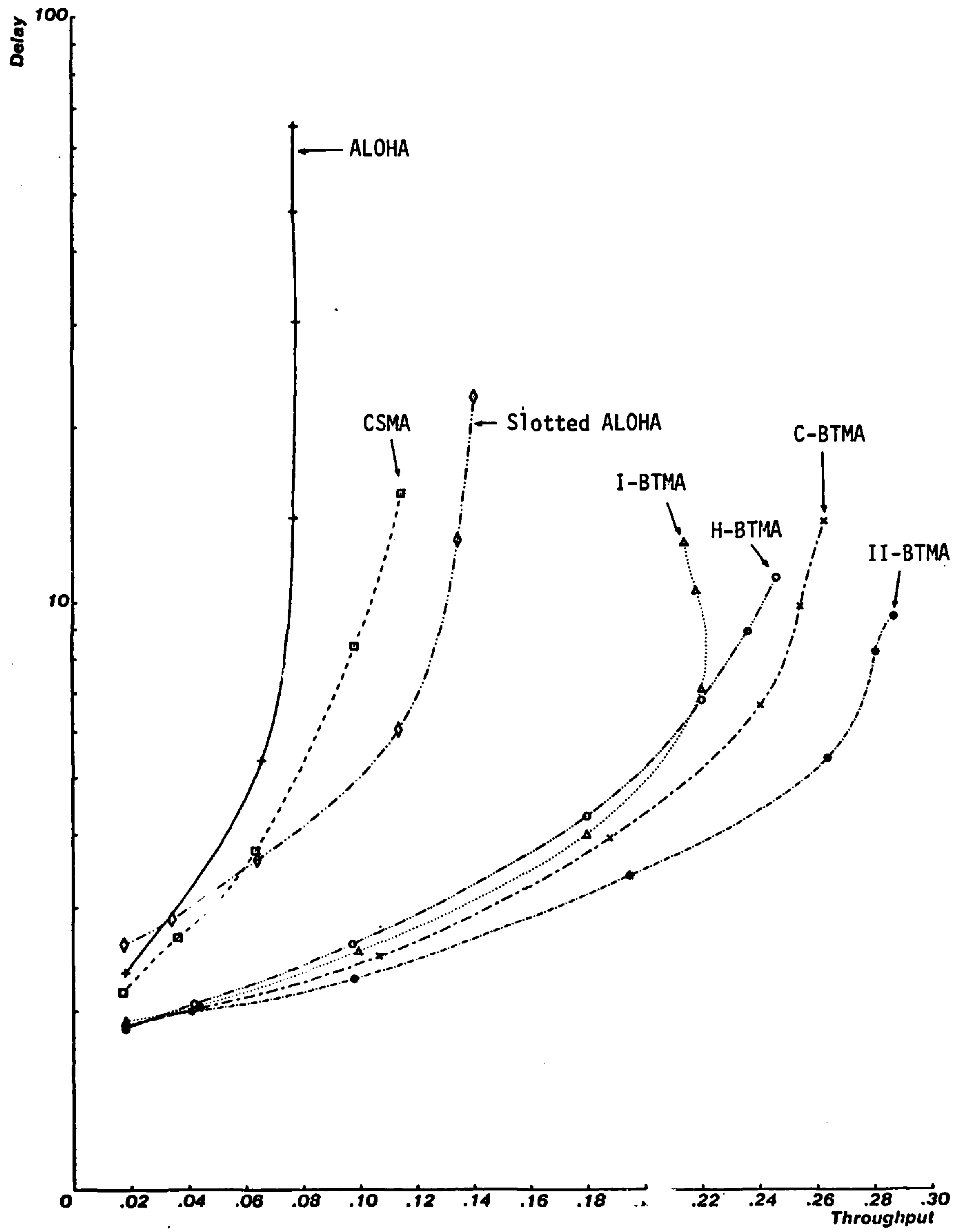

Fig. 18: Envelope of delay versus throughput for the different schemes.

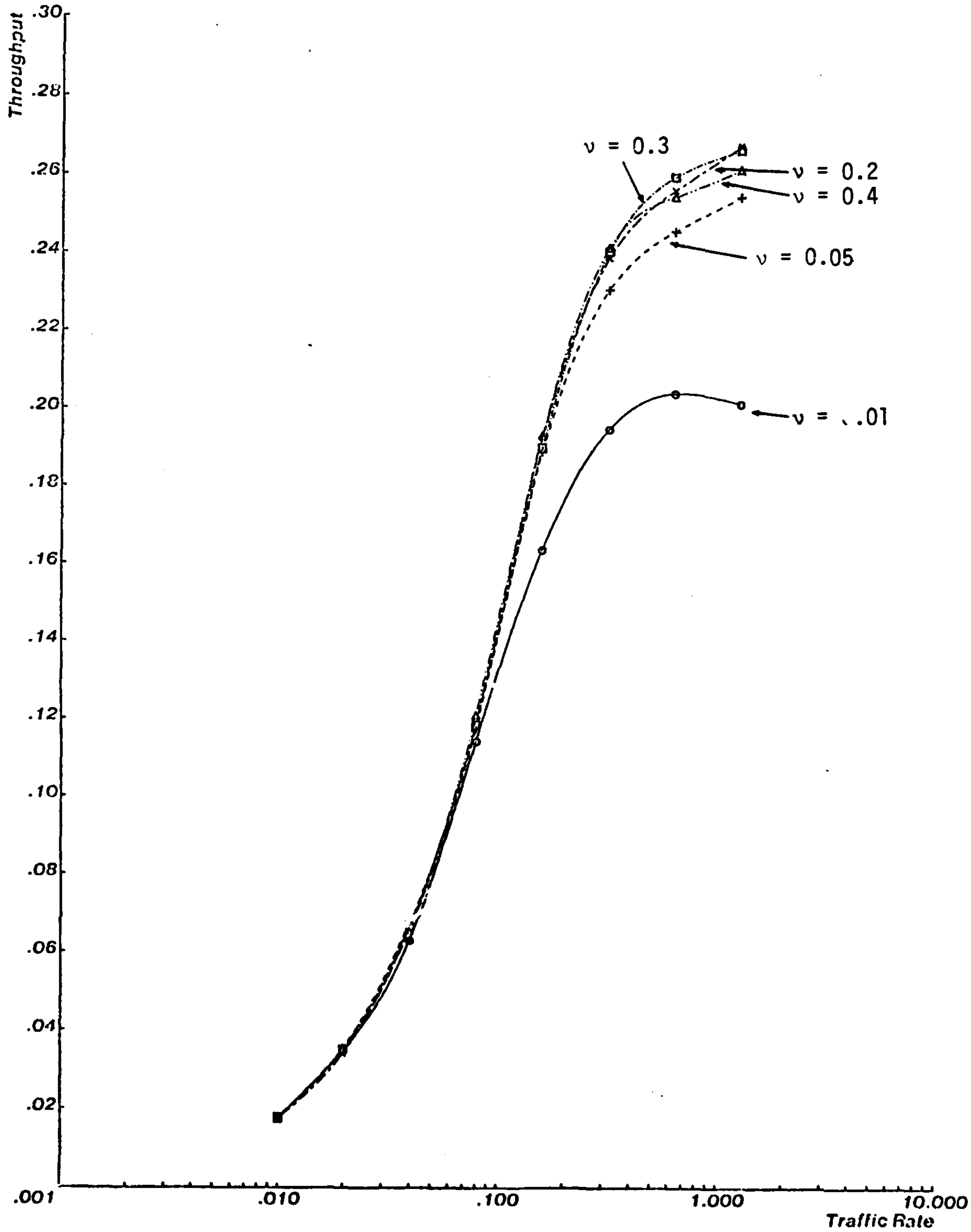

Fig. 19: Throughput versus input traffic rate for CDMA-ALOHA for different values of ν.

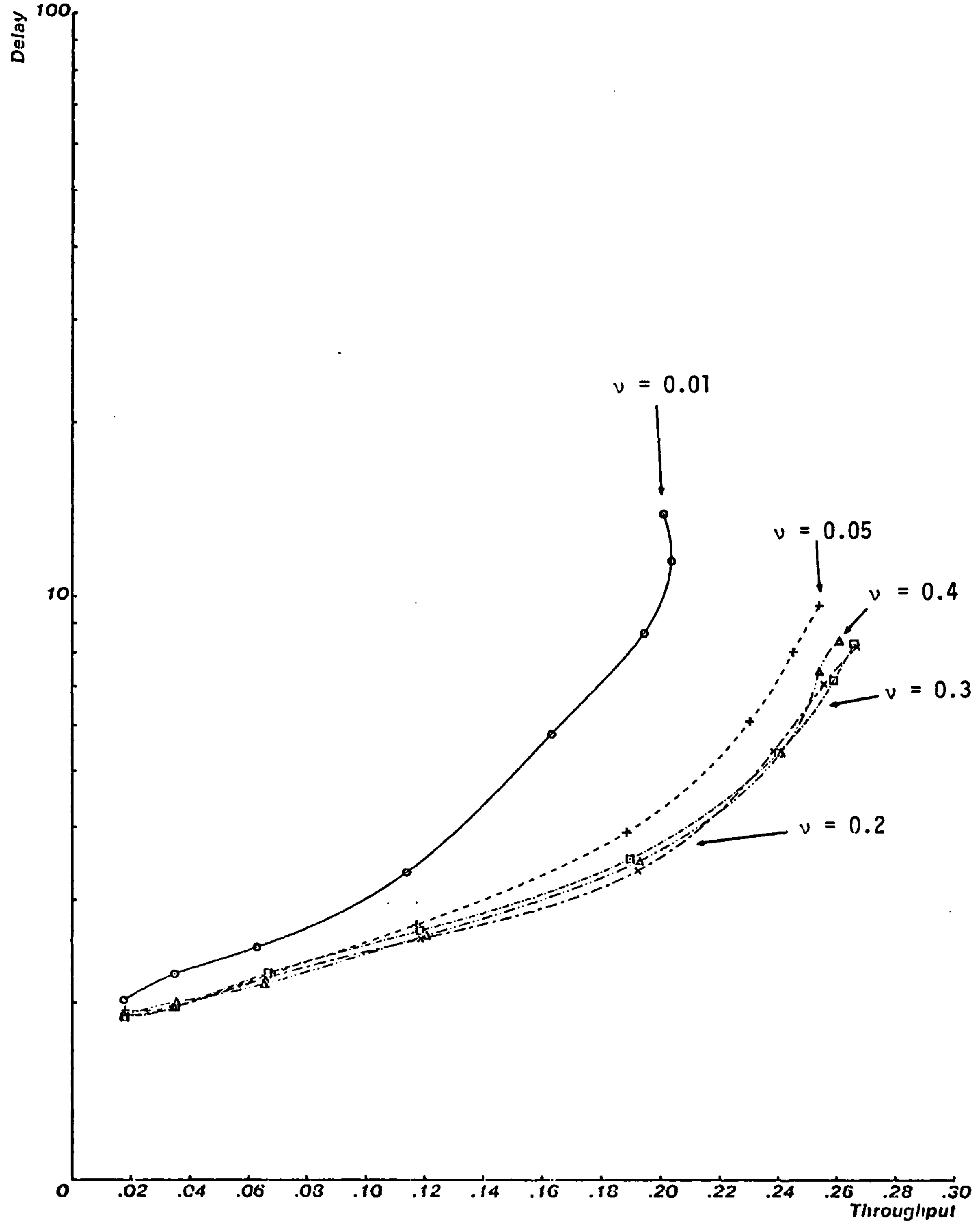

Fig. 20: Delay versus throughput for CDMA-ALOHA for different values of ν.

and a throughput of 0.27 at a delay of 8 is seen to be achievable. Recall that for this scheme perfect capture is assumed to be in effect. We should note that these results should not be directly compared to the previous ones, since in addition to the perfect capture assumption, by implementing CDMA using spread spectrum waveforms the bandwidth is increased by some large factor (typically between 16 and 128 depending on the system requirements [19]). Comparison with the other narrow-band schemes requires perfect understanding of the network resources (the bandwidth, in particular), their cost, their allocation, and the intended objectives of the system. It is still of considerable interest however, to obtain the performance of this scheme.

5.3 Conclusions

We have examined several channel access schemes, namely, ALOHA, CSMA, BTMA and CDMA in the context of multihop packet radio systems. An example of a six node ring was considered to derive numerical results. For this example, it was shown that C-BTMA, which is relatively easy to implement, achieves significantly better performance than ALOHA and CSMA schemes. In particular, it achieves a factor of 2.5 increase in throughput over CSMA. The results presented di l not take into account any bandwidth associated with the use of a busy tone channel. However it is expected that the significant improvement in bandwidth utilization achieved by BTMA in environments with hidden nodes, may well more than compensate for the cost of the busy tone channel.

Appendix 1: The Simulation Software

In previous sections we have discussed the formulation of a model for simulation and described its constituent variables. In this appendix, we discuss the implementation of our model, the validation of the simulation software and estimation of the performance statistics.

The simulation software is written in the Pascal language for a DEC-2060 computer, running under the TOPS-20 operating system. The program is portable and should be able to run on a variety of machines with only minor changes to the I/O routines. The program is also modular in structure and extendible. Changes to accommodate new protocols for example, would involve modifications to one or two procedures *without affecting the rest of the simulation.*

The program utilizes the event driven technique rather than the synchronous timing technique for advancing the simulation clock. The reasons for this are efficiency in CPU utilization and ease of programing. In the event driven method the program is thought of as a finite state machine whose state is updated upon the occurrence of certain events. To implement this, the simulator needs to keep track of an event heap from which the events are obtained and to which events are added. The next event input to the system is the minimum time-ordered event on the heap. The occurrence of each event causes the simulator clock to be advanced by a variable amount.

Data Structures:

The backbone of the program consists of two data structures: the event heap and an array containing the network nodes.

The event heap has often in the past been implemented as a linear list or priority queue [11]. Such structures have $0(n)$ insertion and deletion characteristics (n being the number of elements in the heap). Since it was noted that the program would execute this code a large percentage of the time, it was decided to selectively optimize this area of the code. Therefore the event heap is implemented as a priority queue having a

partially ordered tree structure [12]. For this case, insertion and deletion is $0(log\ n)$, implying significant savings in execution time.

Each node in the array of network nodes is implemented as a Pascal record called repeater. Within each record are fields comprising a FIFO queue (implementing the nodal buffer capacity) and a set of flags indicating whether or not a collision has occurred, the number of carriers sensed, the number of busy-tones sensed, etc. Packets are stored in the queue and the state of the various flags is used to determine whether or not to transmit and whether or not collisions have occured.

The events are implemented as record types having fields for the type of event, the time of the event and the node associated with this event (among others). The event types consist of new arrivals, begin transmits, end transmits, begin receives, end receives, end of processing header, begin of receive of busy tone, and end of receive of busy tone.

The packets are implemented as records containing the fields origin, destination, immediate receiver, packet length and generation time.

Program Structure:

We attempted to structure the program in accordance with the principles of software engineering. The primary guiding heuristic was to partition the code into modules with specific purposes. The program architecture was layered so that abstract higher level functions could be based on a set of primitives in a lower layer. For example, in the program there is an event heap manipulation module and a buffer manipulation module (which manipulates the queues of packets) both essentially autonomous from the rest of the program. There is also a program layer of event handler routines which use primitives imbedded in a lower layer.

The Generation of Packets:

New packets are generated according to a Poisson process. This is implemented by taken a new generation time to be the current system time plus a time generated

according to the exponential probability distribution.

Estimating the Performance Measures:

The objective of the simulation is to obtain values of delay and throughput when the system is in steady state. Hence consideration needs to be given to the initial transient period. In fact since data gathered during the transient period are clearly not representative of the steady state, this data should be discarded. In practice the transient period can only be estimated from measurements and may vary depending on the load and protocol involved. Two methods of dealing with this were employed. Firstly data was ignored for a "warmup" period that was longer than any expected transient period. Secondly enough data was collected so that transient effects would not be observable even if they were present.

It is desirable when estimating statistical parameters to give confidence intervals for the estimates. In the system under study, this could perhaps be accomplished in two ways:

(i) Repeat the run a fixed number of times

(ii) Use the method of regenerative simulation.

Method (i) can be expensive since the cost of a single run may be considerable and so multiple runs could prove prohibitive. In addition the transient data would be wasted in each run.

Method (ii) is to be preferred when the cycle time between returns to the representative state is not too long. For our example, since there are 13^6 states, this does not hold, and so this method cannot used.

Due to the expense involved in method (i), we do not give confidence intervals for our estimates. However we do have a heuristic measure for their validity. This is the fact that the choice of the sample size was made by inspection of a set of results with the size being increased until the statistics appeared to be stationary.

Validation of the Simulation:

It is vital that our software be a correct representation of the simulation model. There are two possible approaches for determining whether this is true or not:

(i) Assuming the physical system corresponding to the model exists, compare the model's performance with measurements of the physical system.

(ii) If an analytical model exists, compare simulation results with those obtained analytically.

In our case method (i) cannot be used, since there is no network built that corresponds to our example. (Indeed, we are hoping that simulation will guide us in the design of such networks.)

The approach of method (ii) was used even though exact analytic solutions were not readily available. We therefore simulated a restricted case where detailed analytical results were available. This was CSMA in a single hop fully connected environment with 50 users. The results for this are given in [10]. For this case a close match between simulated and analytical values for delay and throughput was obtained. However few analytic results exist for the multihop case. In [5] we find that the maximum throughput for a 6 node ring under the pure ALOHA protocol with $a = 0$ is 0.08. This compares well with the simulated maximum value of 0.078 for $a = 0.01$ as ALOHA is insensitive to the propagation delay (the vulnerable period of a packet is the entire transmission time). For C-BTMA with $a = 0$, [5] gives a maximum throughput of 0.333. The largest value obtained from simulation is 0.26. The difference between these two values is attributed in the main to the non-zero propagation delay to which CSMA and BTMA are sensitive (it is related to the vulnerable period of the packet). In addition the simulation curves have not quite achieved a maximum, due to the fact that the system enters a deadlocked state at very high input rates.

In conclusion we believe that the simulator has produced results that compared well with analytical results that were available.

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